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Synergy between HEP and R&D on Matter in Extreme (NNSA)

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Introduction

Big bangs come in different flavors. In high-energy physics (HEP) and nuclear physics, as much energy as possible is packed within individual electrons, protons or heavy nuclei, and their collisions are used to recreate scenes close to the beginning of the universe and time. Nuclear explosions produce another kind of big bang, which not only involves many times more electrons, protons and heavy nuclei, but also requires ‘proper arrangement of atoms’ initially. The performance of materials in the latter scene, a scene of nuclear big bang, is vital to a broad spectrum of DoE/NNSA’s national security science missions. Creating big bangs is only a part of the story in both cases, however. Abilities to measure and characterize the scenes are equally important and challenging. Both a high intensity source of illumination, typically X-rays, electrons and protons, and detectors are indispensable to enable the measurements.

A combination of a 42-keV X-ray free-electron laser (XFEL), a 12-GeV electron beam (Figure 1) and an 800-MeV pulsed proton beam has been proposed for the Los Alamos MARIE (short for MATter-Radiation Interaction in Extreme) experimental facility to study dynamics of material evolution related to the nuclear big bang. The peak brilliance of the proposed 42-keV source for

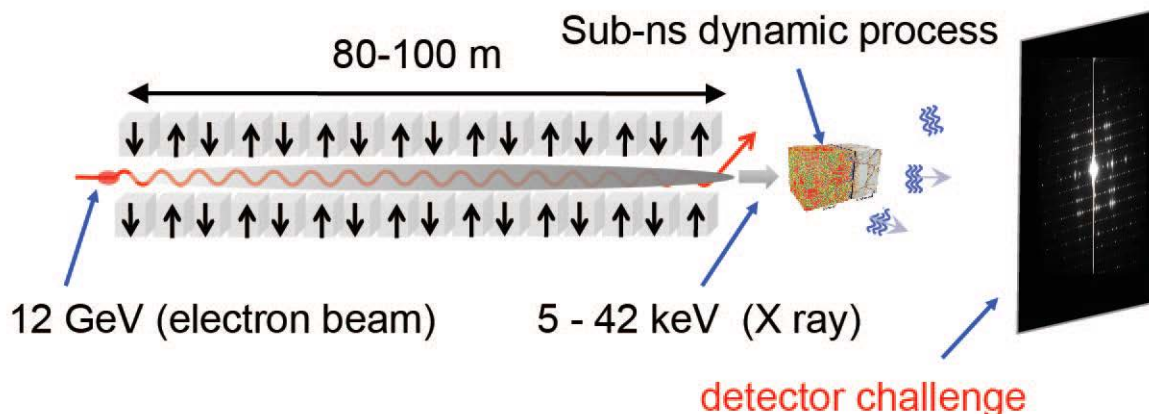


Figure 1. Coherent X rays with energies up to 42 keV are proposed to image sub-ns dynamic processes in the Los Alamos MARIE facility. No technology exists today however that can meet all the detection requirements in a single device.

MARIE can reach one billion times that of a third-generation source like the Advanced Photon Source (APS) at Argonne National Laboratory. With their unprecedented brightness, superior penetrating power to visible light, sub-ps temporal resolution, and well understood physics of matter interactions, XFELs are uniquely positioned to create movies of structure formation and phase transitions at nano- and meso-scales and open up new vistas into matter in extreme. No technology exists today, however, that can make such movies without compromise at least one way or another (lower frame rates, insufficient detection efficiency, inadequate temporal resolution, too coarse spatial resolution, *etc.*). The need for better X-ray and neutron detectors, as well as better charged particle detectors, which can take full advantage of the sources like the existing and future XFELs has also been recognized, for example, in the 2012 DoE/BES report on X-ray and neutron detectors.

Semiconductor detectors, in particular silicon-based detectors, have revolutionized X-ray imaging. The existing semiconductor technologies used in X-ray facilities can be traced back to past research and development pioneered in HEP decades ago. Meanwhile, the new challenges in picosecond (detector response time), gigahertz (frame rate), efficient hard X-ray imaging for MARIE-class facility would require new concepts, alternative materials to silicon, further advances in electronics (FPGA, ASICs) and possibly optical data handling capabilities. We would like to emphasize sub-nanosecond scintillators and GHz ASICs as two examples of HEP research that can play important roles in the on-going and future matter-in-extreme research.

X rays, as well as energetic charged particles, can induce luminescence or visible light emission in many materials, a phenomenon known as radio-luminescence. The materials are called scintillators, which can come in such diverse material forms as single crystals, poly-crystals (ceramics), amorphous solids (glasses, powders, plastics), liquids (organic and inorganic solvents loaded with fine particles that scintillate) and gases (Ar and Xe, for example). The history of scintillators is at least as old as that of X-rays. Wilhelm Röntgen discovered X-rays because of X-ray-induced scintillation in barium platinocyanide. Scintillators are intrinsically fast materials for ultrafast (picosecond) hard X-ray detection and imaging since photons rather than electrons are used in the first stage of X-ray-to-signal conversion and signal propagation.

HEP Context

HEP has a long history of using and developing heavy crystal scintillators for precision electromagnetic calorimeters. Tens of cubic meters of high quality crystals were produced after rigorous R&D carried out by the HEP community in a close collaboration with crystal growers. Examples are BGO crystals for the L3 experiment in the eighties, Ti:CsI crystals for the BaBar experiment in the nineties and PWO crystals for the CMS experiment during the decade crossing the century. In the last decade R&D on the Ce:LYSO crystals were carried out by the HEP community. As a result Ce:LYSO is chosen to construct future crystal calorimeters at the energy frontier, such as the CMS forward calorimeter upgrade, and the intensity frontier, such as the Mu2e experiment at Fermilab and the SuperB factory.

Future HEP experiments at the energy and intensity frontiers require very fast crystals to cope with the unprecedented event rate. Table 1 summarizes basic properties of fast crystal scintillators, including oxides (LSO/LYSO), halides (BaF₂, CsI and CeF₃) and the recently discovered bright and fast halides (CeBr₃, LaCl₃ and LaBr₃) as well as a typical plastic scintillator. All the fast halides discovered recently are highly hygroscopic so that their application needs extra engineering work. Among the non-hygroscopic crystal scintillators listed in Table 1, BaF₂ crystals with a sub-nanosecond fast decay component produce the highest scintillation photon yield in the 1st nano-second, just less than the highly hygroscopic CeBr₃ and LaBr₃. This fast component provides a solid foundation for an extremely fast ECAL made by BaF₂ crystals. In addition to the good energy resolution and fast response time the photon direction measurements are also important for neutral pion identification through its two photon decays. Most crystal calorimeters built so far has no longitudinal segmentation because of the technical difficulty of imbedding readout device in a total absorption calorimeter. With compact readout devices developed in the last decade this issue is less relevant now. A well designed segmented ECAL with fast crystal detectors

may provide excellent energy resolution, fast timing and fine photon angular resolution, so would serve well for the future HEP experiments in general and those at the intensity frontier in particular.

Table 1 Basic Properties of Fast Crystal Scintillators

	LSO/LYSO	GSO	YSO	CsI	BaF ₂	CeF ₃	CeBr ₃ ¹	LaCl ₃	LaBr ₃	Plastic scintillator (BC 404) ²
Density (g/cm ³)	7.40	6.71	4.44	4.51	4.89	6.16	5.23	3.86	5.29	1.03
Melting point (°C)	2050	1950	1980	621	1280	1460	722	858	783	70 [#]
Radiation Length (cm)	1.14	1.38	3.11	1.86	2.03	1.70	1.96	2.81	1.88	42.54
Molière Radius (cm)	2.07	2.23	2.93	3.57	3.10	2.41	2.97	3.71	2.85	9.59
Interaction Length (cm)	20.9	22.2	27.9	39.3	30.7	23.2	31.5	37.6	30.4	78.8
Z value	64.8	57.9	33.3	54.0	51.6	50.8	45.6	47.3	45.6	-
dE/dX (MeV/cm)	9.55	8.88	6.56	5.56	6.52	8.42	6.65	5.27	6.90	2.02
Emission Peak ^a (nm)	420	430	420	420 310	300 220	340 300	371	335	356	408
Refractive Index ^b	1.82	1.85	1.80	1.95	1.50	1.62	1.9	1.9	1.9	1.58
Relative Light Yield ^{a,c}	100	45	76	4.2 1.3	42 4.8	8.6	141	15 49	153	35
Decay Time ^a (ns)	40	73	60	30 6	650 0.9	30	17	570 24	20	1.8
d(LY)/dT ^{a,d} (%/°C)	-0.2	-0.4	-0.1	-1.4	-1.9 0.1	~0	-0.1	0.1	0.2	~0

- a. Top line: slow component, bottom line: fast component.
b. At the wavelength of the emission maximum.
c. Relative light yield normalized to the light yield of LSO
d. At room temperature (20°C)
#. Softening point

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Chenliang Li et al, *Solid State Commun*, Volume 144, Issues 5–6 (2007), 220–224
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http://pdg.lbl.gov/2008/AtomicNuclearProperties/HTML_PAGES/216.html

Impact

The on-going effort of the HEP community to develop very fast (sub-ns) crystal scintillators fits well with what the Los Alamos MARIE needed. Following visits of Dr. Zhehui Wang to Caltech and Dr. Ren-Yuan Zhu to Los Alamos it is recognized that the experience and expertise of the HEP community in developing high quality crystal scintillators are valuable assets for the proposed MARIE detector development of NNSA. A joint R&D program is under discussion with initial samples prepared by Caltech and to be tested at Los Alamos.

The new imagers using a fast-scintillator frontend can also be tested and used in the on-going experiments at APS and LCLS (the Stanford XFEL). Currently, the temporal resolution of dynamical process imaging using synchrotron X rays at APS are at least tens of nanoseconds, partly limited by the decay times of scintillators like LSO:Ce. LCLS can overcome the limitation for single-frame imaging by delivering sub-ps X-ray pulses. But with the energy of 8 kV, the LCLS X-rays do not have sufficient penetrating power for most high-Z and thick targets. The initial new X-ray imager could aim at single-frame hard-X-ray (above 15 keV) imaging with a temporal resolution close to or below 1 ns, X-ray detection efficiency above 50%, and a spatial

resolution below 500 microns. Single crystals of YAP: Yb and BaF₂ can be used as the imager frontend that converts X-rays to visible photons. Detection efficiency above 50% can be readily obtained for a scintillator thickness about 1 mm and X-ray energy up to 42 keV. Besides ASICs, commercial ICCD, EMCCD cameras can also be used as the backend in the first experiments. The commercial photocathodes can be selected for the CCD cameras to match the characteristic UV and visible emissions from the scintillators. For example, the photoelectric efficiency above 30% can be obtained for the 220 nm UV photons emitted by BaF₂, which is the fast component of BaF₂ scintillation. For longer wavelength visible photons, higher efficiency can be obtained. Built upon the initial development on timing and efficiency, pixelated scintillator detectors can be designed, constructed and tested next for 100 micron or better spatial resolution. Finer detector spatial resolution will allow more flexibility in choosing the distance between the object and the imaging plane, for example.

Joint detector development between HEP and matter-in-extreme research will be very desirable and mutually beneficial. Both fields have common interests in developing effective fast scintillators discussed above. Similar statements can also be made for ASICs. The development takes time and requires special expertise. There are HEP groups working on technologies that can be either directly used or upgraded to meet the needs in both fields. One example is the PSEC4 chip.

The R&D issues for fast crystal detectors include the following two aspects. (1) Suppressing the slow scintillation component in BaF₂ by selective doping and/or selective readout by using solar blind photo-detector, and improve the radiation harness of BaF₂ crystals by reducing oxygen contamination. (2) Development of novel fast scintillators with sub-nanosecond decay time, e.g. Yb:YAP, Yb:Lu₂O₃, PbFCl, CuI and Ga:ZnO etc.

The continued demand for fast crystal scintillators in large quantities for HEP applications has certainly stimulated the research effort to develop newer and better materials as well as to improve the performance of existing materials. Because of the large quantity cost-effectiveness of the material is crucial for HEP applications. In addition, the severe radiation environment expected in the HEP environment requires radiation hard materials. These are the unique elements provided by the HEP related R&D efforts. Since the same material also has industrial usages, the R & D result obtained in HEP research will have a direct impact in industrial applications.

The search and development for new materials is an expensive and time-consuming process with high risks. The era for industry to put money and effort to do fundamental material research has long gone, and such tasks require governmental support. HEP has led such effort in the past that has been matched by any other field. For the future development, close communications and involvement with relevant industrial partners would remain the key to ensure that successful development in HEP and other fields can be transferred to industry. Technology transfer will result in cost savings for HEP programs, stimulate industry growth in the mean time and thus be mutually beneficial to all parties.